APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.

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14. ABSTRACT
The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

15. SUBJECT TERMS

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3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To design and conduct an experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides an actual laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The network consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the NPAL network.

The second avenue includes highly focused, comparatively short-term experiments.
We are currently planning a major experimental effort in the Philippine Sea. Again the primary institutions will be APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Earlier this year a Pilot Study/Engineering Test was conducted in the Philippine Sea to characterize the environment and to test new hardware and software systems. During this effort we also provided support to researchers from the Marine Physical Laboratory (MPL) who are supported by the signal processing code of ONR. The main experimental effort in the Philippine Sea will begin in the Spring of 2010, and is outlined in Figure 2.

As we have prepared for the next major experiment, funding from the Defense University Research Instrumentation Program (DURIP) has provided significant support. In particular, this report includes activities funded by two DURIP grants (N00014-08-1-0797 and N00014-08-1-800).

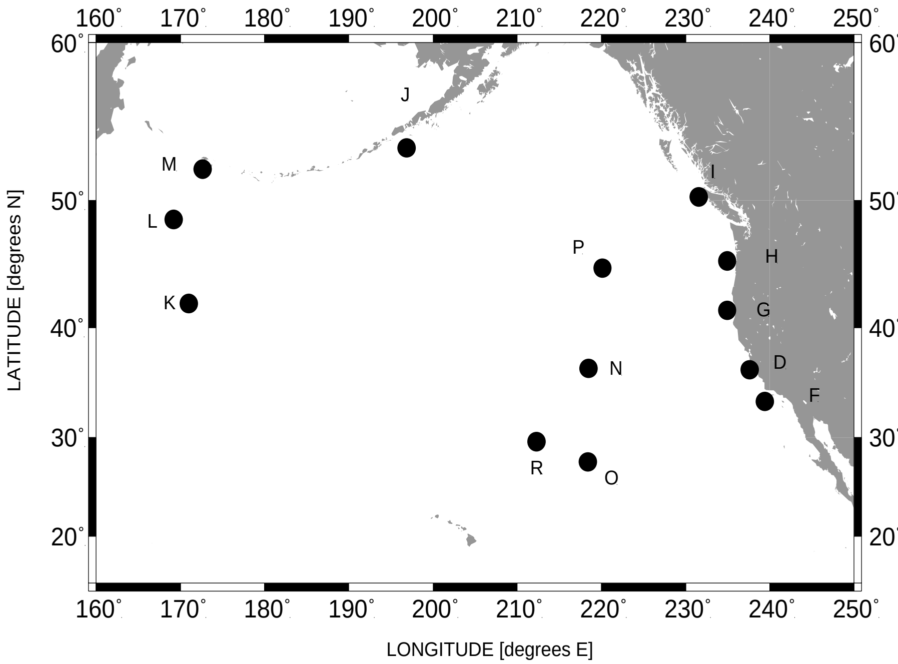

Figure 1. The NPAL hydrophone array network. The locations of arrays identified by the letters R, D, E, and F are exact. The other locations are notional. The entire network is controlled and monitored from APL-UW.

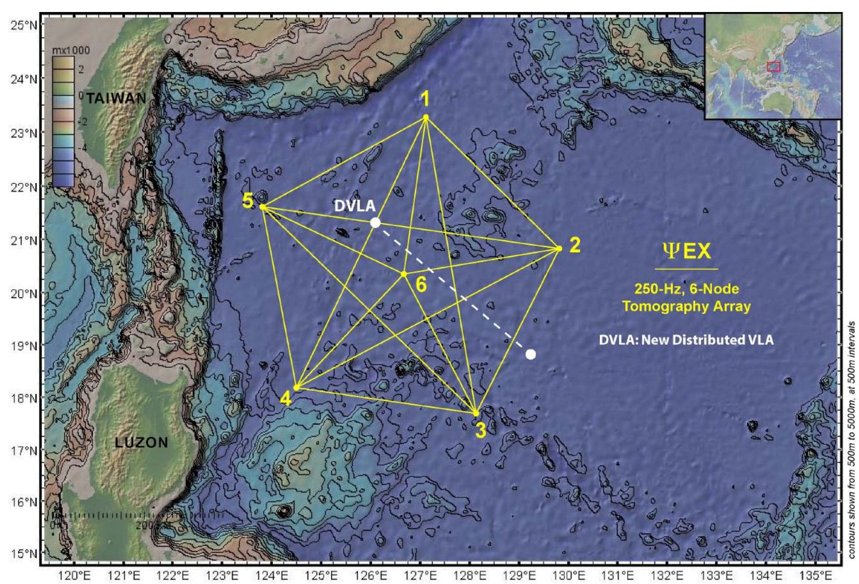

Figure 2. The 2010 Philippine Sea Experiment; the yellow lines are tomography paths between acoustic transceivers, the DVLA is a full water column hydrophone array, and the dashed white line is a 500 km path for continuous broadband transmissions along which extensive environmental data will be collected.

WORK COMPLETED

NPAL Acoustic Network. A paper titled "Long-Time Trends in Low-Frequency Oceanic Ambient Noise along the Western North American Coast" was revised and submitted to the *Journal of the Acoustical Society of America.* A paper titled "A decade of acoustic thermometry in the North Pacific Ocean" was published in the *Journal of Geophysical Research*.

LOAPEX Analysis. The Long-range Acoustic Propagation EXperiment (LOAPEX) was conducted by APL-UW in 2004 and is still producing journal articles. A paper titled "LOAPEX: The Long-range ocean acoustic propagation experiment" was published in the *IEEE Journal of Oceanic Engineering*. A paper titled "The interference component of the acoustic field in the Long-Range Ocean Acoustic Propagation Experiment" was published in the *Journal of the Acoustical Society of America*. A paper titled "Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation" was published in the *Journal of the Acoustical Society of America*.

Philippine Sea Pilot Study/Engineering Test. The APL-UW portion of the Philippine Sea Pilot Study/Engineering Test, known as PhilSea09, was conducted between 14 April and 1 May 2009. The exercise area is shown in Figure 3.

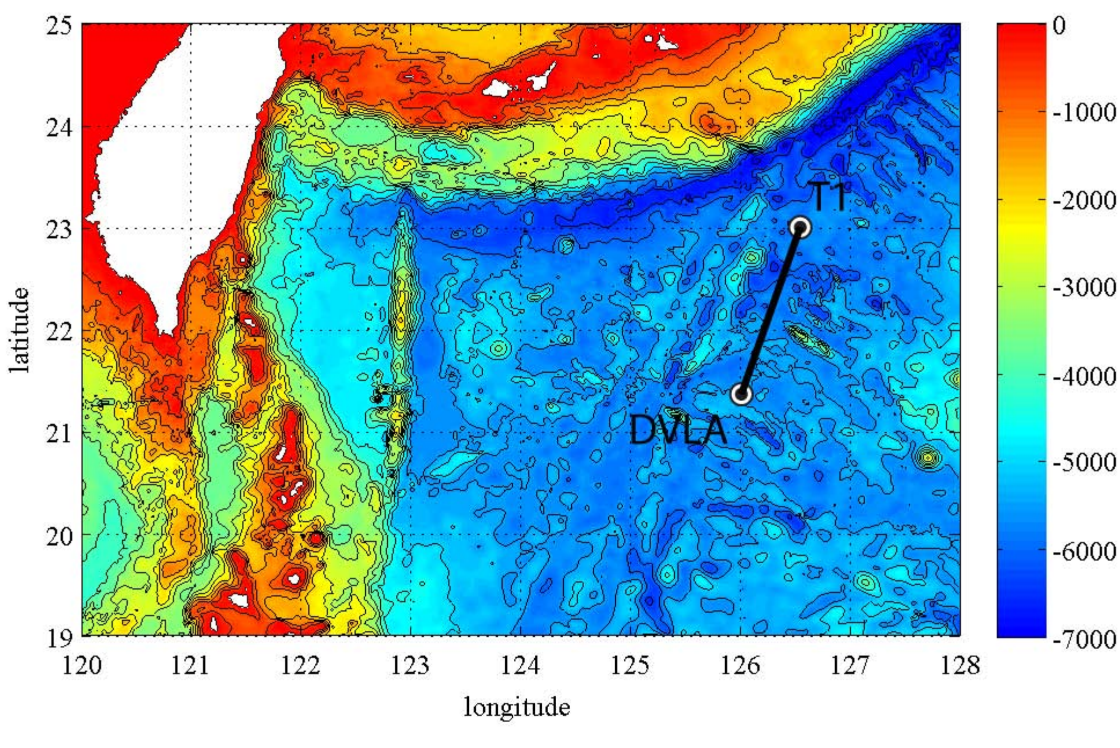

Figure 3. The exercise area for PhilSea09.

The DVLA, indicated in Figure 3, was a prototype for the full-water-column array and included an axial sub-array and a near-bottom sub-array. APL-UW suspended acoustic sources at ranges of 47 and 107 km from the DVLA and collected environmental data along the path (black line) and beyond the DVLA.

The locations of environmental data collected by APL-UW are shown in Figure 4.

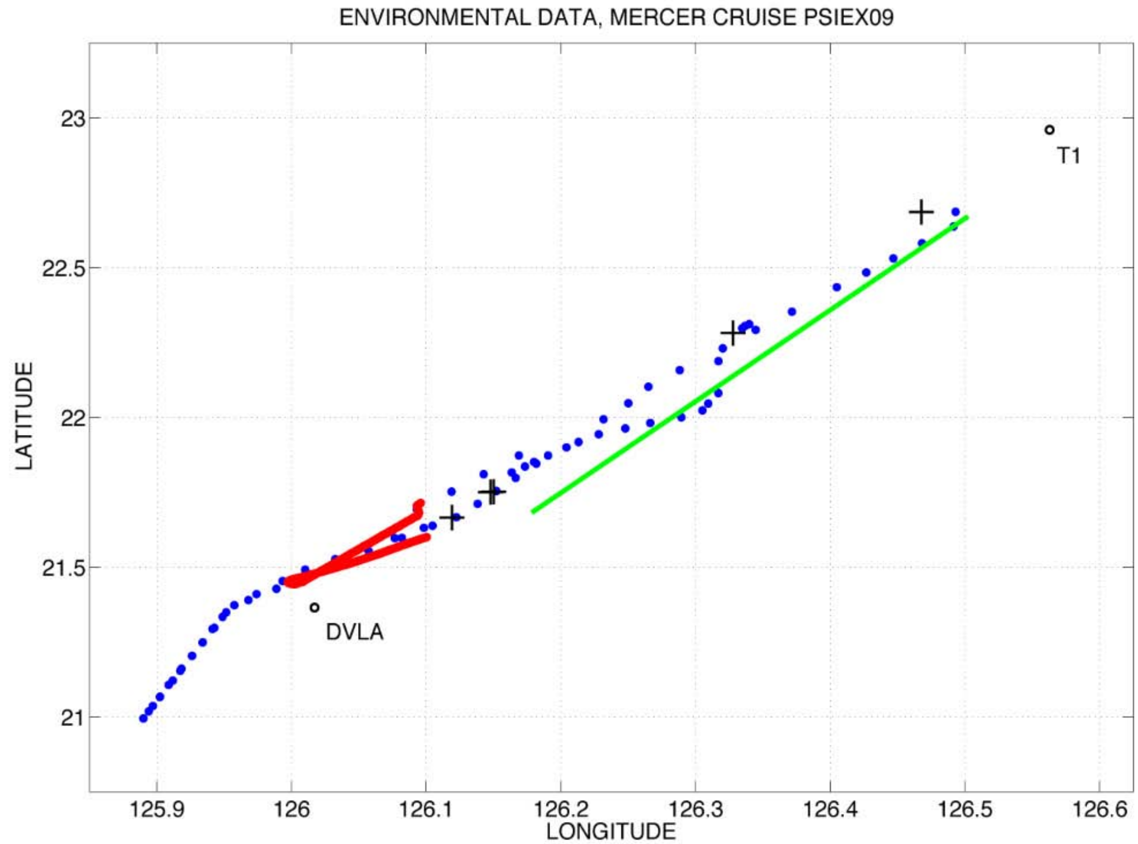

Figure 4. Locations of environmental data collected during PhilSea09 (aka PSIEX09). The blue dots represent the locations of XBT drops, the black plus symbols are locations of conventional CTD casts, and the red and green lines represents paths for the new towed CTD Chain.

The Philippine Sea Experiment (PhilSea10). Conceptual plans for PhilSea10 were finalized in September of this year. SIO will install the tomography array and DVLA in April of 2010 and they will operate for a full year until their recovery in 2011. APL-UW will conduct suspended source operations at a range of 500 km from the DVLA totaling 110 hours of continuous transmissions at a depth of 1000 m. The transmissions will be divided equally between the HX source operating at a center frequency of 80 Hz and the MP source operating at a center frequency of 260 Hz. The HX source will also be used at 50 Hz while drifting at a depth of 150 m between ranges of 25 to 35 km from the DVLA. In addition, APL-UW will conduct extensive CTD casts between the DVLA and the 500 km test position and also tow the CTD Chain along this path. During July of 2010 the MIT/WHOI group will tow a J-15 acoustic source at various ranges from the DVLA.

Instrumentation for the Philippine Sea Experiment – DURIP (N00014-08-1-0797). This DURIP grant provided a number of instruments to improve the reliability and safety of our field work. Signal durations in the Philippine Sea were extremely long, on the order of 50 hours. The generation of long-duration, high-power acoustic signals required new instrumentation including a broad-band amplifier and low-level signal generation hardware and software. The detailed design of the experiment (e.g., depths and ranges to the other assets) required extensive computer simulations to be conducted with a parabolic equation acoustic propagation code, and a numerical model of the effective acoustic scattering. To accomplish these simulations a small computer cluster was purchased. The requirement to precisely navigate the location and velocity of the projectors was met with an acoustic tracking system. The control and data logging features of this system also provided for the recording of the projector internal temperature and pressure.

To accomplish these long transmissions some new instrumentation components were required. The first was a new power amplifier. Our existing power amplifier was damaged in an electrical storm and was not capable of providing power across the entire frequency band of the HX and MP transducers. An L50 power amplifier from Instruments Inc. was purchased to meet our requirement.

In general, the type of acoustic transmissions used in our work are either broad band phase-coded, maximal-length binary sequences, or source compensating frequency-multiplexed non-linear slides. These signals are generated from specialized hardware and software. Our existing signal generation equipment was based on a 15-year-old 80486 PC running DOS, an obsolete National Instruments data acquisition (DAQ) board, and a custom discrete logic timing board. The signal waveform output must be synched to a precision GPS clock, providing microsecond timing accuracy, via the timing board, the DAQ, and custom software. Components which have failed over the years have been replaced with parts salvaged from other systems. There were no more such spare salvaged components available. All components, with the exception of the timing board, were utterly obsolete, so there was no option to purchase replacement parts. Continuing dependence on this system would result in a total loss of transmission data in the increasingly likely event that any aging part should fail. A replacement signal generation system was required.

We upgraded our signal transmission capability by replacing our aging and obsolete 80486/DOS computers with 80686/Linux systems. A key component of this upgrade has been replacing the old National Instruments AT-MIO-64F5 data acquisition cards with National Instruments PCI-6071E cards (purchased with an earlier DURIP grant) and finding/installing/integrating corresponding device drivers. We selected the open-source drivers from COMEDI over the new National NIDAQmx Linux drivers because (a) the National driver was essentially ported from the COMEDI community, and (b) the COMEDI driver is delivered as source code, whereas the source for the National driver is proprietary and not available. Source code availability was critical during development, as it enabled us to match our requirements through to the hardware capabilities by rendering transparent the operations from user space to kernel space to hardware features documented in the NI manuals.

The goals of our experimental method were to combine high resolution environmental data with precisely controlled geometries for acoustic transmissions. The accurate navigation of our deployed sources is a critical element in computing coherence functions for our received signals. We needed to be able to separate signal de-coherence caused by source-motion Doppler, from that due to the ocean variability related Doppler. The best and most straightforward method of navigation down to 1000 m depths is an acoustic tracking system. In PhilSea09 we used existing acoustic transponders and deployed them on the bottom about our source positions and with this DURIP developed tracking system that interrogates the bottom-mounted transponders and receives their replies. This tracking system was located in the immediate vicinity of the acoustic projector. The heart of the system is a Teledyne Benthos ATM-885 modem board that comes with a suitable tracking transducer, and a Persistor CF2 controller and data logger. As an inexpensive method of obtaining the source depth, we incorporated a pressure sensor on the tracking system pressure case. We purchased a Paroscientific pressure transducer and integrated it into the system. This data was recorded in the tracking system data logger and sent to the surface via the fiber link. There was some concern about the internal temperature of the acoustic sources. Because of the very long transmission durations it was considered prudent to have a method of monitoring the internal temperature of the sources. To this end, a small temperature probe was mounted inside the source transformers and the resulting signal was sent to the tracking system pressure case where was recorded and sent to the surface via the fiber link. All tracking and sensor data were recorded in the tracking system pressure case so that breakage of the optic fiber would not be catastrophic.

Towed CTD Chain – DURIP (N00014-08-1-0800). A major focus of the Philippine Sea Pilot Study/Engineering Test was a study of the physics related to the performance of acoustic propagation models and the models that ultimately describe the ocean sound speed and its variability. The Philippine Sea is a highly energetic region and a detailed knowledge of this environment was required to develop and test both environmental and acoustic propagation models. Variability in the sound-speed structure due to internal waves, neutrally buoyant sound-speed perturbations, internal tides, and mesoscale eddies and fronts will produce large fluctuations in the received signals reducing the temporal and spatial coherence. Although we sampled the water with conventional in-situ instrumentation such as conventional CTDs and XBTs, the best and a more synoptic measurement could be obtained by deploying a Towed CTD Chain directly along our propagation path. The goal was to eliminate uncertainty about the sound-speed description when comparing acoustic data and model outputs. To this end we ordered a Towed CTD Chain System from ADM-Electronik (Germany). The main elements of the system are illustrated in Figure 5.

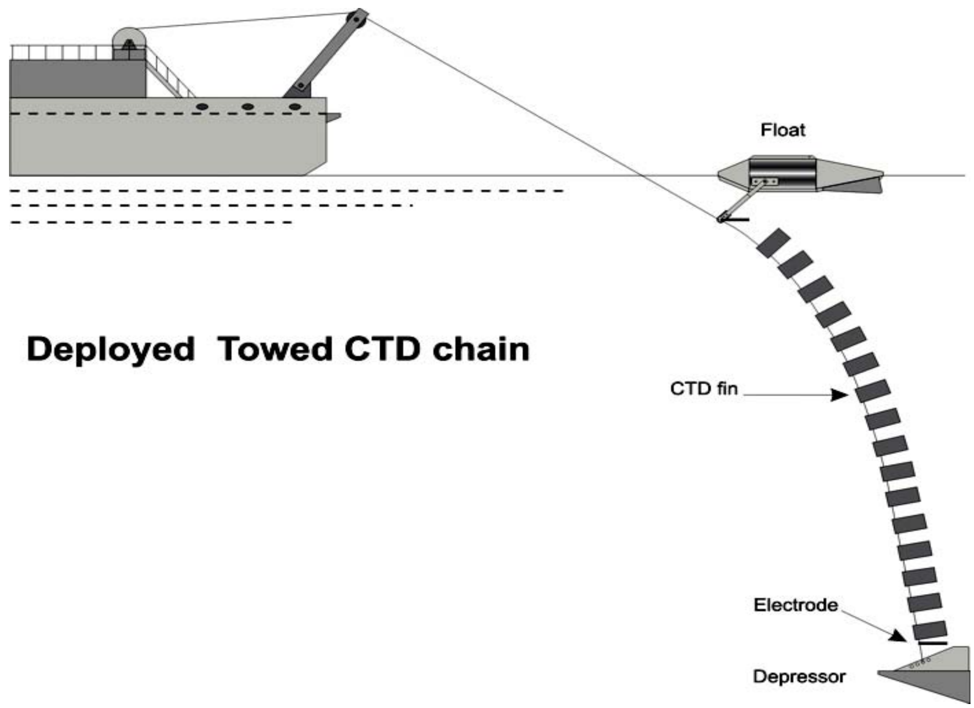

Figure 5. Main components of the Towed CTD Chain.

RESULTS

The addition of the Optical/Electrical/Mechanical for suspending our acoustic sources allowed several new capabilities. For example, temperature sensors in the acoustic sources indicated that the sources were not overheating during the very long transmission sequences. In addition, pressure sensors near the sources provided very accurate depth information and a hydrophone channel allowed us to monitor and calibrate the source without having to suspend another cable from the ship. Finally, an acoustic navigation system, controlled over the fiber, but located near the sources, provided location information on the sources while they were deployed. Figure 6 illustrates the quality of the acoustic tracking that was achieved. This figure compares acoustic tracking (the thin line in each frame) with positions based upon the leased C-Nav GPS system. The C-Nav GPS system has an accuracy of 10 cm and its antenna was placed directly over the block from which the acoustic source was suspended. The upper two frames in Figure 6 compare the east and north tracking solutions for a period of about 15 minutes. The slight phase shift between the acoustic and GPS data is expected because the source is several hundred meters below the ship and it takes a short time for the source to “feel” the ship motion. The bottom frame compares the vertical motion of the source as computed acoustically with the vertical motion of the GPS antenna over a period of only 120 seconds. Because the source is suspended with a steel cable they move up and down together. The location as determined by the GPS was shifted to overlay with the acoustic data. The heaving of the ship can be seen clearly in both data sets.

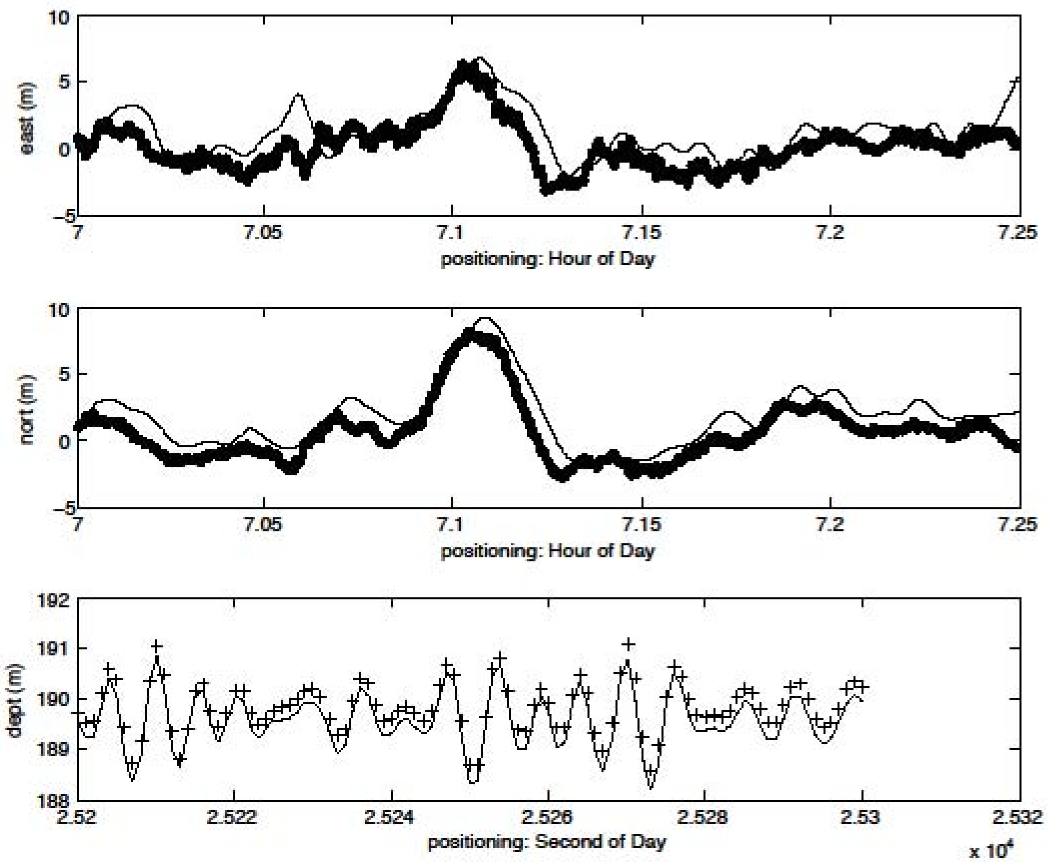

Figure 6. A comparison of source tracking via acoustics (thin line) and the C-Nav GPS system. The top frame is motion in the east-west direction, the middle frame in the north-south direction, and the bottom frame in the vertical direction.

During the Pilot Study/Engineering Test (PhilSea09) acoustic transmissions were performed at two ranges from the DVLA, 47 and 107 km. Figure 7 presents a reception from the MP source on the DVLA at a range of 47 km. The vertical axis is depth, and the horizontal axis is time in seconds. In effect, the figure shows a time front sweeping across the axial sub-array. The reception shown includes only one M-sequence. Normally, many sequences would be averaged together coherently to increase the signal-to-noise ratio, but even a single sequence is clearly observed here. In this case the MP source was at a depth of 1000 m. No corrections have been made yet for the motion of the array or the motion of the source. Once these corrections are made, a movie of the receptions over several hours will reveal the effect of ocean sound speed perturbations on the acoustic time front. The dark bands in the figure reveal areas on the DVLA where the hydrophones are separated by 75 m instead of the 25-meter spacing for the central part of the axial sub-array.

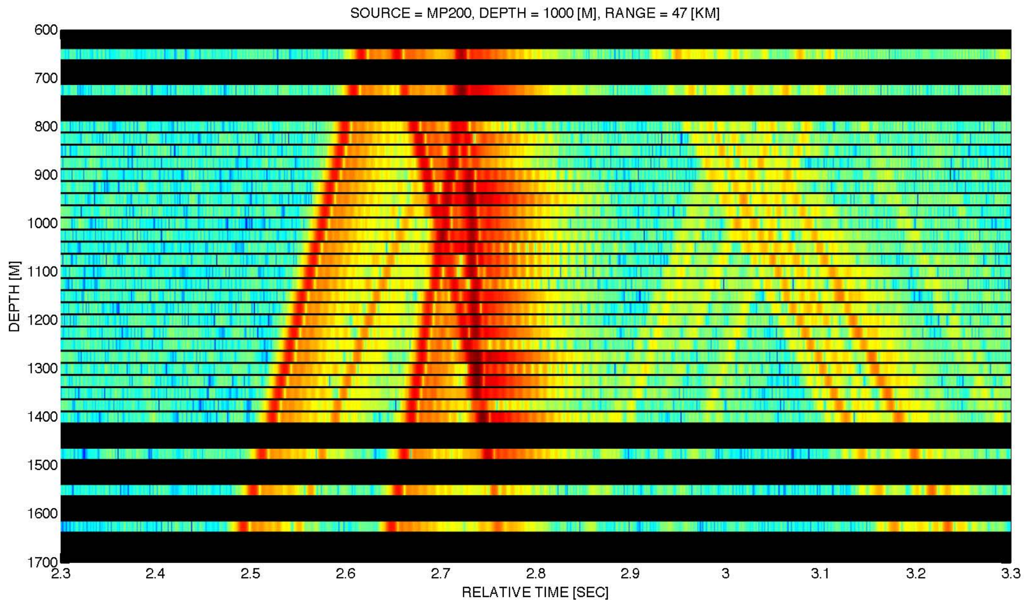

Figure 7. A time front reception on the axial sub-array of the DVLA. The source was the MP source at depth of 1000m at a range of 47 km. Only one M-sequence is displayed in this reception. The source band width is approximately 230 to 330 Hz.

Figure 8 presents results from typical CTD data collected during a) LOAPEX, and b) PhilSea09.

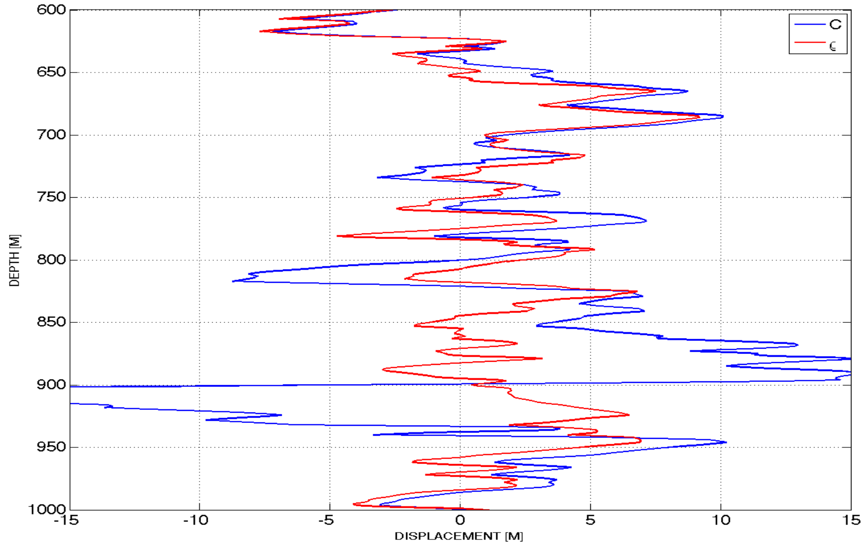

Figure 8a. Density displacements (red) and sound speed displacements (blue) vs. depth from a typical CTD cast taken during LOAPEX.

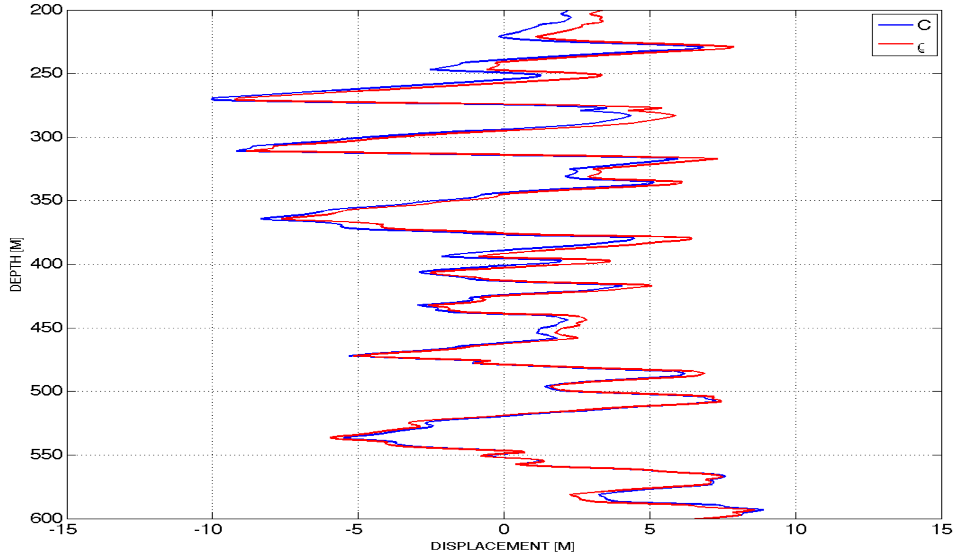

Figure 8b. Density displacements (red) and sound speed displacements (blue) vs. depth from a typical CTD cast taken during PhilSea09

Due to the fact that the Philippine Sea is a highly dynamic region of the global ocean, we expected to find a significant internal wave field and a significant spice field. Spice refers to water masses that are density compensated but have an altered sound speed compared to the standard water mass at the same depth. For example, a water mass that is warmer and saltier than the surrounding water will have a different sound speed, but may have the same density, and therefore be stable at that depth. The relative displacements of density and sound speed shown in Figure 8a from LOAPEX allow one to infer that significant spice is present. The similar data in Figure 8b from PhilSea09 do not suggest the presence of spice.

The difficulty in quantifying spice is due to the fact that it does not propagate as internal waves do. For internal waves, a single mooring with many sensors throughout the water column can provide a great deal of information about internal waves in the region of the mooring. The horizontal spectrum of spice cannot be measured this way. To this end we deployed and towed the CTD Chain illustrated in Figure 5.

The CTD Chain used in PhilSea09 has 88 individual CTD fin instruments on the inductive cable. A deck interface sent a signal to all 88 fins at once causing each fin to simultaneously lock in measurements of conductivity, temperature, and pressure (depth). The interface then polled each fin, one at a time, to retrieve its data. This entire process was repeated every two seconds. Figure 9 presents results from a tow approximately 10 nm miles long. The figure plots ocean temperature as a function of pressure (depth) and the tow period which lasted about 2.5 hours.

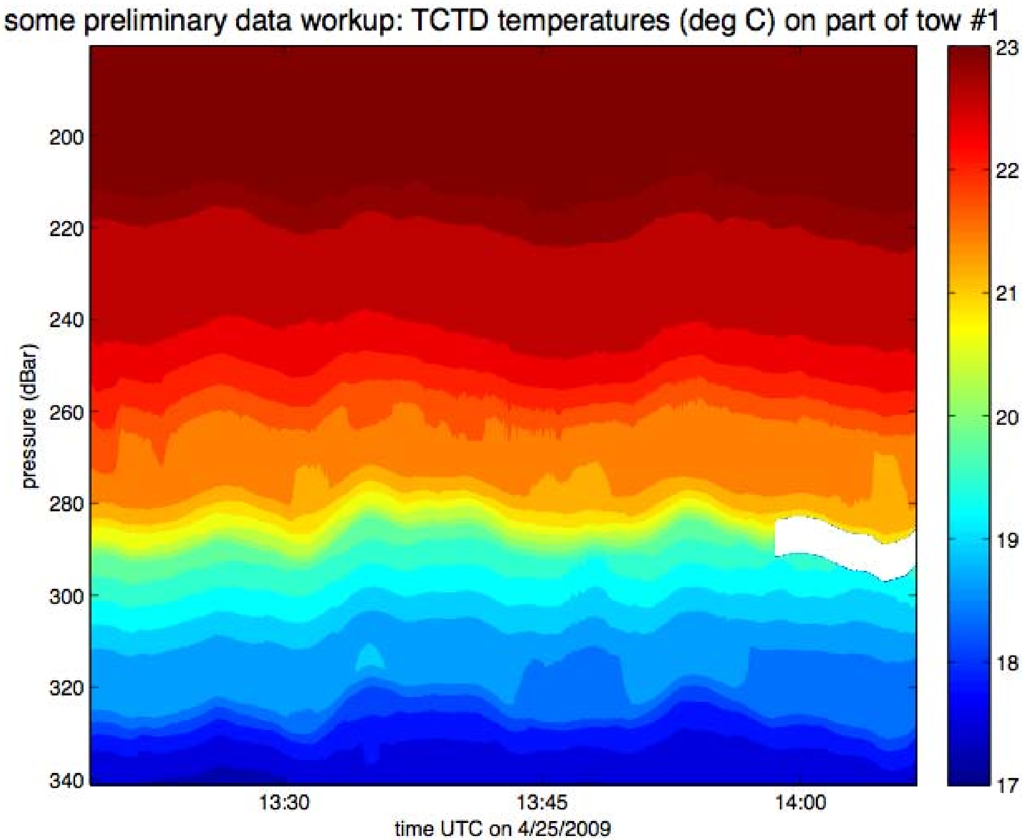

Figure 9. Towed CTD Chain temperature data from PhilSea09 vs. pressure (depth) and the tow period (about 2.5 hours). The temperature scale at right is in degrees Centigrade.

As a back up to the CTD casts and the towed CTD Chain data, roughly 100 XBT drops were made during PhilSea09. XBT probes measure the water temperature as they fall through the water column. The temperature data is sent to the surface on a very fine copper wire. Unfortunately the probes are not highly accurate and any estimates of the sound speed require an assumption about the salinity profile. Furthermore, the depth of the temperature data is based upon an assumption about the rate at which the probe falls through the ocean. This rate can be affected by the currents in the water and by the friction on the spools which deploy the copper wire. We used primarily two types of XBT probes during PhilSea09, T5s and T7s. T5s work to a depth of 1800 meters, while T7s work to a depth of 750 meters. Figure 10a compares temperature data versus depth for both T5 (green) and T7 (blue) probes. Also in the figure is a dotted red line that shows the temperature results from a PhilSea09 CTD cast. There is a significant difference between the T5, T7, and CTD temperature data. Figure 10b shows the same data after fall rate corrections have been made for the XBT probes.

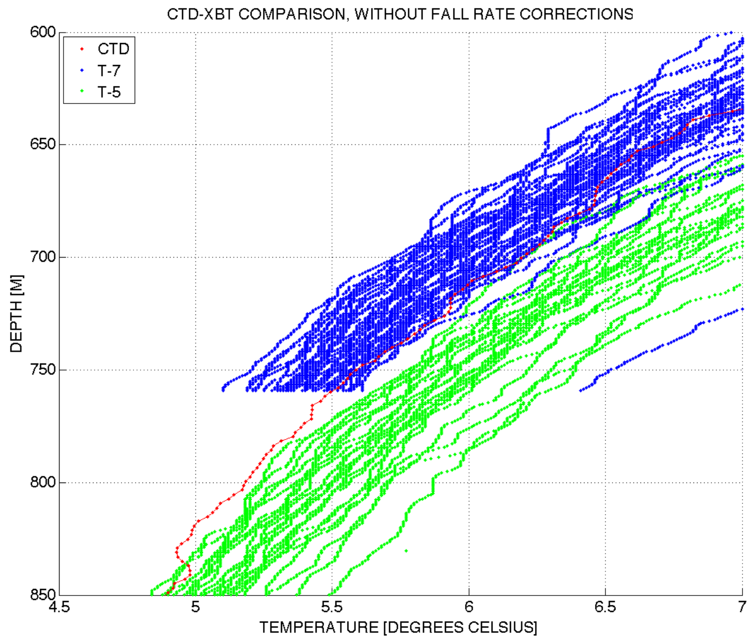

Figure 10a. Uncorrected Philsea09 XBT data. T5 (green) and T7 (blue) XBT temperature data vs. depth compared to temperature data from a CTD cast (red).

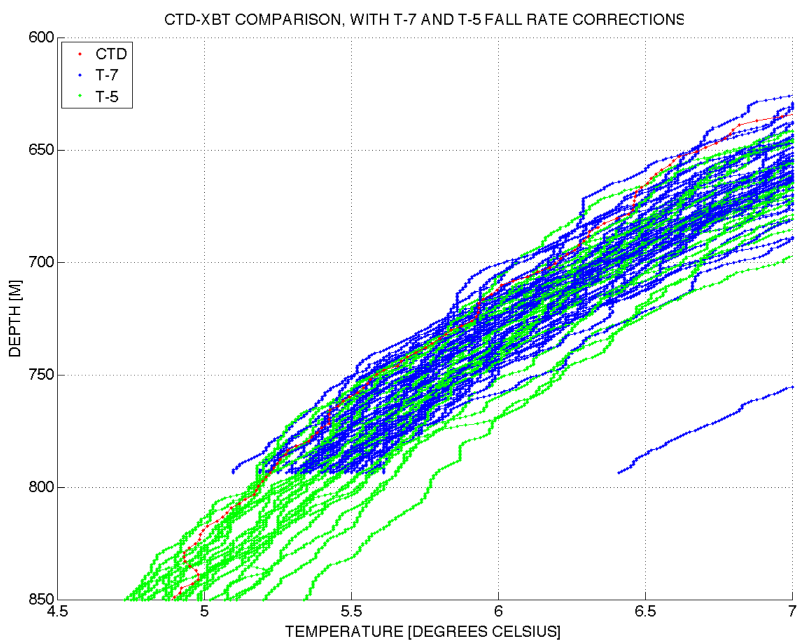

Figure 10b. Corrected PhilSea09 XBT data. T5 (green) and T7 (blue) XBT temperature data vs. depth corrected for fall rate. CTD data (red).

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

RELATED PROJECTS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), M. Wolfson (APL-UW), G. Zaslavsky (NY Univ.), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

PUBLICATIONS

Stephen, R. A., Bolmer, S. T., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Buck, L. J., Mercer, J. A., Colosi, J. A., and Howe, B. M., (2009). Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation, *J. Acoust. Soc. Am.,* **126**, 599-606. [refereed]

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